# A versatile thermoelectric temperature controller with 10 mK reproducibility and 100 mK absolute accuracy

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We describe a general-purpose thermoelectric temperature controller with 1 mK stability, 10 mK reproducibility, and 100 mK absolute accuracy near room temperature. The controller design is relatively simple and could be readily modified for use in different experimental circumstances. We also describe a time-domain numerical model that allows one to characterize the stability and transient behavior of the system being controlled, even in the presence of elements with highly nonlinear responses. © *2009 American Institute of Physics.* [doi:10.1063/1.3274204]

Thermal management is an important aspect of many scientific experiments, and the need to accurately control the temperatures of multiple devices becomes more acute as experiments become ever more sophisticated. Three aspects of temperature control should be considered: (1) absolute accuracy—the ability to set the temperature of a system to a desired value; (2) reproducibility—the ability to set the temperature to the same value repeatedly, even if the actual value of the temperature is not precisely known; and (3) stability—the ability to keep the temperature at a constant (although perhaps not well known) value without temporal drifts.

Electronic temperature controllers have been described by numerous authors in the past,[1–4] and considerable attention has been given to achieving a very high temperature stability in the system being controlled. In our own experiments investigating the molecular dynamics of crystal growth,[5] we are frequently less interested in stability than in reproducibility, absolute accuracy, and a well-behaved transient response. To meet our requirements, we have developed and numerically modeled an adaptable, general-purpose temperature controller that uses thermistors as sensing elements and thermoelectric modules to heat or cool in the $-40$ to 40 °C range.

A schematic of our controller is shown in Fig. 1, which is an adaptation of the design reported in Ref. 1. We first look at the specifications of several different electronic components.

Our controller was designed to use a general-purpose calibrated thermistor probe that is absolutely accurate to $\pm 0.1$ °C over the temperature range 0–70 °C and to $\pm 0.2$ °C down to $-40$ °C.[6] The probe resistance is approximately 2300 Ω at room temperature, but we operate more typically in the temperature range 0 to $-20$ °C, where the resistance runs from 7–21 kΩ, increasing roughly 5.4% for each degree Celsius temperature decrease.

The thermistor is placed in a bridge with a Vishay S Series 10 kΩ high-precision foil resistor that has a resistance tolerance of $\pm 50$ ppm and a temperature coefficient of $\pm 2$ ppm/°C. Comparing these specs with the thermistor sensitivity of 5.4% per degree, the equivalent temperature error from the reference resistor tolerance is roughly $\pm 1$ mK, and the drift in temperature set point with resistor temperature is $\pm 40$ $\mu$K per degree.

The bridge is driven by a Burr-Brown REF102BP-ND 10 V precision voltage reference, which has an output of $10 \pm 0.0025$ V and a drift of $\pm 2$ ppm/°C. The former produces an equivalent temperature measurement error of $\pm 9$ mK, and the latter gives a maximum drift of $\pm 70$ $\mu$K per degree.

Both the temperature and set point sides of the bridge are monitored using Analog Devices OP07CPZ-ND operational amplifier (op-amp) buffers. These each have an input offset voltage of $\pm 75$ $\mu$V and an input bias current of $\pm 2$ nA. Assuming a bridge voltage of 5 V, the former gives an equivalent temperature error of $\pm 0.5$ mK, while the bias current introduces temperature errors of $\pm 0.2$ mK. The input resistance is at least 10 MΩ, which results in equivalent temperature errors as high as $\pm 10$ mK. The input offset voltage drift is $\pm 2$ $\mu$V/°C, which produces an equivalent temperature drift of $\pm 10$ $\mu$K per degree.

The two sides of the bridge are compared using an Analog Devices ADANZ-ND instrumentation amplifier with the gain set to $G = 100$, to give the error-signal voltage

$$V_{\mathrm{err}} = G V_{\mathrm{ref}} \left[ \frac{R_{\mathrm{set}}}{R_{\mathrm{pot}}} - \frac{R_T}{R_{\mathrm{ref}} + R_T} \right], \tag{1}$$

where $V_{\mathrm{ref}} = 10$ V, $R_T$ is the thermistor resistance, $R_{\mathrm{ref}} = 10$ kΩ is the reference resistance, and $R_{\mathrm{set}}$ is the resistance of one side of the ten-turn potentiometer that has a total resistance of $R_{\mathrm{pot}} = 20$ kΩ.

The error signal feeds a standard servo with proportional and integral gain. A Burr-Brown OPA544T-ND op-amp, with a maximum output current of 2 A, drives a thermoelectric module that changes the temperature of the system to complete the feedback loop.

The bridge produces two outputs: a temperature monitor (Mon A in Fig. 1) and a set point monitor (Mon B). A switch chooses which output is sent to a *BNC* monitor output together with a 3.5 digit panel meter. A 5 kΩ trimmer is used to produce a well-defined ratio between the panel meter output and the monitor voltage. We chose the parameters so that

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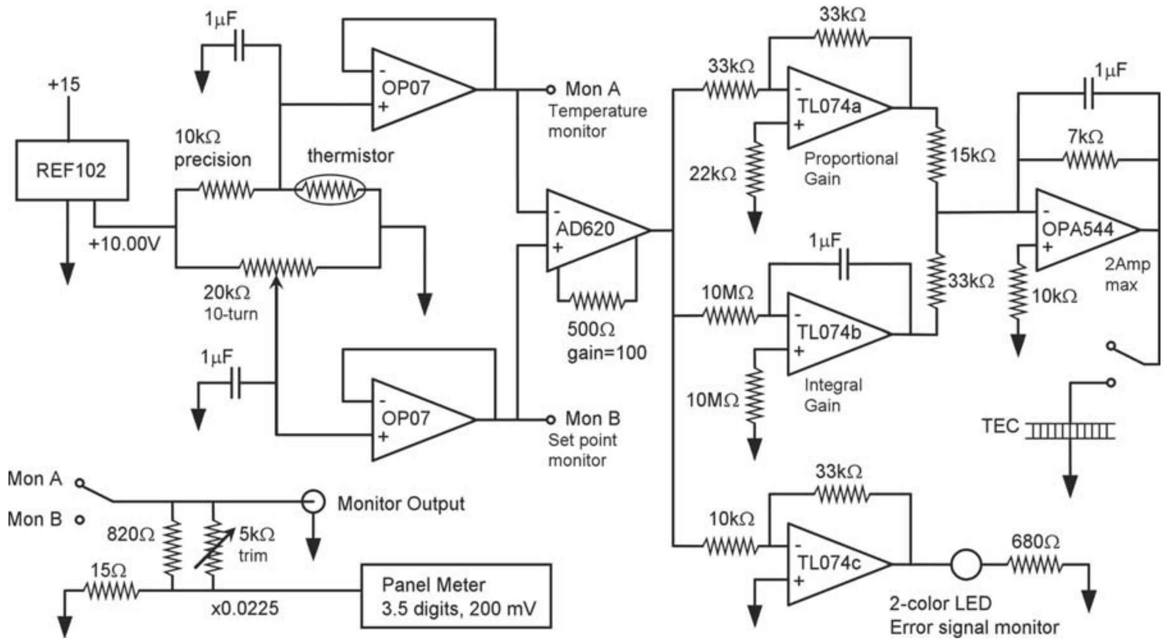


FIG. 1. Schematic diagram of the temperature controller. A thermistor serves as the sensing element, and a thermoelectric device (TEC) is used to heat and cool the system being controlled. A panel meter is used to monitor the set point as well as the actual system temperature.

one digit on the panel meter corresponds to a temperature change of $\Delta T \approx 0.05\ ^\circ\mathrm{C}$ during typical operation, which is well-matched to the absolute accuracy of the thermistor. The dual-monitor feature has proven especially convenient in operation, since one can easily view the set point and the system temperature with good accuracy using the panel meter. When still higher accuracy or reproducibility is desired, a precision voltmeter can be used to measure the monitor voltages via the *BNC* output.

In our experiments we typically change temperatures frequently, so it is beneficial to have a controller with a fast and well-behaved transient response. To achieve this we created a useful time-domain numerical model that reproduces the behavior of our controller over a broad range of conditions, thereby allowing us to optimally adjust the circuit parameters for different experimental systems.

The numerical model begins with the temperature of the system we are controlling, from which we derive the thermistor resistance from an interpolation of tabulated values supplied by the manufacturer. From this, it is straightforward to calculate the response of the various circuit elements in Fig. 1 to produce the power op-amp output voltage that drives the thermoelectric module. In addition to the controller response, our model also requires the thermal response of our system. For testing purposes, we used a minimal setup consisting of (1) a $30\times 60\times 1\ \mathrm{cm}^3$ aluminum base plate at ambient temperature; (2) a $4\times 4\times 0.5\ \mathrm{cm}^3$ aluminum test plate with a pair of thermistors mounted inside the plate; (3) a single thermoelectric module sandwiched between the base plate and test plate; and (4) insulation to shield the test plate from ambient air currents. We determined the thermal response of the test plate by applying fixed voltages to the thermoelectric module and observing the temperature as a function of time. The response was well reproduced by the functional form

$$T_{\mathrm{system}}(t) = T_0 + \Delta T(1 - e^{-t/\tau}), \tag{2}$$

where $T_0$ is the test plate temperature with no applied voltage. For our specific test plate we determined $\tau \approx 130\ \mathrm{s}$ and $\Delta T \approx 5.5\ \mathrm{V} + 0.17\ \mathrm{V}^2$ in degrees Celsius, where $V$ is the voltage applied at $t=0$, in volts. Notable features of this response include: (1) a single time constant, independent of $V$ that will depend on the thermoelectric modules used and the thermal mass of the system and (2) a temperature difference $\Delta T$ that exhibits a nonlinearity in $V$, indicating that thermoelectric heating is more effective than cooling (because of power dissipation in the modules). This relatively simple exponential thermal behavior is typical for systems driven by thermoelectric modules. The time constant $\tau$ provides the main source of high-frequency roll-off in the overall loop gain of the servo system.

From this observed behavior we can write the model algorithm

$$T_{\mathrm{system}}(t+\Delta t) = T_{\mathrm{system}}(t) + [T_0 + \Delta T(V) - T_{\mathrm{system}}(t)]\frac{\Delta t}{\tau} \tag{3}$$

using the voltage $V$ applied at time $t$. From this and the controller response, we use simple Newtonian numerical integration in the time domain to generate the test plate temperature $T_{\mathrm{system}}(t)$ for future times, starting from known initial conditions.

Figure 2 shows one example comparing model and measured behaviors of our test system. In this case we had removed the integral gain and turned up the proportional gain until the servo was on the verge of oscillating. With no adjustments, our model would not show oscillatory behavior at any proportional gain, so we added a small time delay in the thermal response, replacing the controller input temperature $T_{\mathrm{system}}(t)$ in Eq. (3) with $T_{\mathrm{system}}(t-\delta t)$. The parameter $\delta t$ was adjusted to reproduce the observed oscillation period in

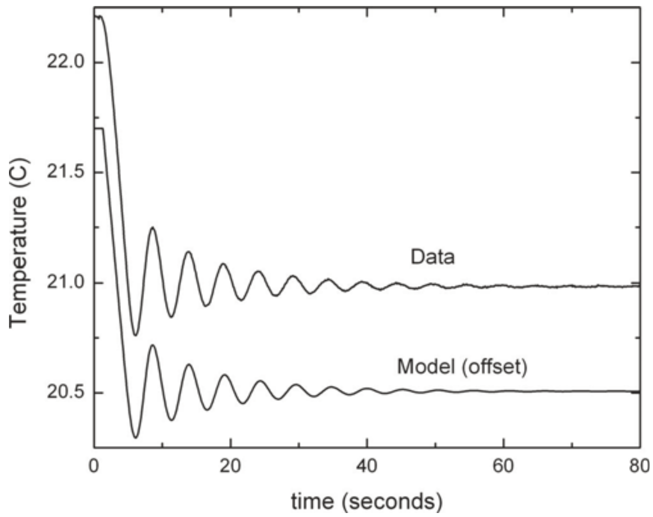


FIG. 2. The response of our test system to a change in temperature set point at $t=0$, in comparison to the modeled behavior. For clarity the model curve was displaced downward by a fixed amount. For this case the integral gain in the controller was set to zero, while the proportional gain was increased until the system was on the verge of oscillating.

Figure 2, giving $\delta t = 1.3$ s. Since $\delta t \ll \tau$, this change had little effect except to induce oscillations at high gains. Other than this short time delay, our model had no adjustable parameters. This same time delay reproduced the operation of our controller in other circumstances without additional adjustment.

We have found that this simple numerical model is quite useful for examining and optimizing the behavior of our temperature controller over a broad range of conditions. Nonlinear behavior, such as when the set point is changed and transient voltages are clipped at their maximum values, is easily included. The model convincingly demonstrated that adding a differential gain stage yielded negligible improvement in system performance, so this was not included in our controller design. In general, once the system thermal response has been determined, this model can be used to predict the transient and possible oscillatory behavior of any experimental system being controlled.

We performed several tests to examine the performance of our controller under normal operating conditions. In one simple test we replaced the sense thermistor with another precision 10 k$\Omega$ reference resistor and measured the temperature monitor output (Mon A in Fig. 1) using a precision voltmeter. With a sample of ten separate controllers we recorded monitor outputs of $V = 5.0000 \pm 0.0004$ V, implying an equivalent temperature accuracy of $\Delta T \approx 3$ mK. The largest deviation in the ten controllers was 0.0008 V, for an equivalent temperature error of 6 mK. These measurements show how well the controller performs as a basic thermometer.

We then used the test setup described above to control the temperature of the aluminum test plate using one embedded thermistor, while we used the second embedded thermistor to monitor the temperature of the plate. The temperature was determined using the monitor output of a second controller that was connected to the second thermistor. We used a sampling of ten pairs of controllers in this test. The difference between the set point and monitor voltages in the drive controller corresponded to a temperature difference of $-6 \pm 60$ $\mu$K, which indicated that this controller was doing its job of bringing the error signal to zero. The temperature difference between the two controllers was measured to be $14 \pm 3$ mK. This difference was surprising in that it is substantially smaller than the rated 100 mK absolute accuracy of the thermistors.

In a final test, we used two controllers as in the previous paragraph and observed a temperature stability of roughly 1 mK over periods of several hours under typical ambient conditions. The stability appeared to be limited mainly by residual air currents on our test setup producing temperature gradients in the test plate.

In summary, we have designed a versatile, general-purpose temperature controller, developed a numerical model of its behavior, and conducted several tests to confirm the calculated performance. The controller is straightforward to build, readily modified, easy to use, and it has proven extremely useful in our laboratory when we wish to control the temperatures of many devices with high absolute accuracy and stability.

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